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13. ABSTRACT *(Maximum 200 words)*

We summarize our fifth quarter results and discuss plans for the remainder of the baseline program which is to demonstrate a thin film edge emitter triode with 10μA/μm emission current density at less than 250V and which can be modulated at 1 GHz for 1 hour. We completed fabrication of the first thin film edge emitter vacuum transistors this quarter. Extensive DC characterization has been carried out. Triode characteristics have been observed on many devices. Low frequency (1 KHz) modulation of the devices has been shown. Parametric testing shows these devices to have the high currents (50μA), high current densities (10μA/mm) and transconductances (1.5μS) necessary to achieve 1 GHz operation. High frequency testing is currently underway.

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Quarterly Technical Report

RF Vacuum Microelectronics

10/01/92 -12/31/92

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RF Vacuum Microelectronics
Quarterly Technical Report
10/01/92 - 12/31/92

I. Background

The objective of the RF Vacuum Microelectronics Program is to establish the technology base for the fabrication of practical, high performance gated vacuum emitters and to develop a new class of RF amplifiers based on these vacuum microelectronic emitters. Our technical approach is to utilize thin film technology and surface micromachining techniques to demonstrate an edge emitter based vacuum triode with emission current density of 10 μA/μm at less than 250V which can be modulated at 1 GHz continuously for 1 hour. Figure 1 shows a schematic cross section of our thin film edge emitter approach.

The edge emitter triode approach offers several potential advantages to achieving high frequency device operation (compared to cone emitters and wedge emitters):

- The fabrication process is a planar process, compatible with most silicon IC manufacturing.
- Thin film processes for the films used in the triode process are well controlled and reproducible. Control of film thicknesses to within 5% for the emitter film thickness is easily attainable resulting in a well-controlled edge emitter.
- Device capacitance for the edge emitter is less than that achievable for cones or wedges resulting in higher frequency operation.

Based on our experience with fabricating and testing edge emitter devices, our efforts on this program will be focussed on developing a highly stable, uniform and reliable current emission from the edge. We intend to achieve these qualities by

- use of thin film (200Å) edge emitters with small uniform radius of curvature
- use of refractory metal emitter structure to prevent electromigration and burnout
- use of comb emitter structures to prevent premature emitter burnout during edge formation
- use of current equalization series elements to set bias currents.

This program to develop an edge emitter triode started on October 1, 1991. The baseline portion of the program is for 18 months with the above mentioned objectives as goals. Upon successful completion of this phase, an option phase for 12 months can be implemented by DARPA with the objective to achieve 10 GHz modulation with the edge emitter device.

II. Technical Progress During Quarter

Key Achievements (10-01-92 to 12-31-92)

- Demonstrated a thin-film emitter transistor with symmetrically layered gate/control electrodes and integrated anodes.
- Demonstrated low frequency (1KHz) modulation of a thin-film emitter transistor for the first time.
- Presented paper on the thin-film edge emitter triode at IEDM in San Francisco.

III. Technical Progress

Task 1.0 Field Emitter Development

This task was completed at the end of the last quarter.

Task 2.0 Process Development

This task was completed at the end of the last quarter.

Task 3.0 Triode Development

Our efforts on the program this quarter were primarily focussed on triode development. Three fabrication runs were completed which incorporated the process enhancements outlined in the Quarterly Technical Report #4. Figure 1 shows an SEM of a completed device. The thin-film 400Å edge is readily observable. The structural integrity of the device looks excellent and agrees well with our design expectations.

We have carried out extensive testing of the vacuum triode devices. Most of the efforts to date have been towards DC characterization of the triodes. Anode current measurements versus control voltage (gate voltage) show as expected triode action. Monitoring the output characteristics versus control/gate and anode voltages indicate little, if any, interception by the gate of electrons emitted by the emitter. This is consistent with previous modeling results (as reported in Quarterly Technical Progress Reports #2 and #3) which show that emitted electrons are controlled predominantly by the anode voltage in a dual control electrode structure.

We have begun modulation testing of the edge-emitter triode devices. Low frequency modulation of a triode has now been shown which is a first for a thin film edge triode.

Attached Figures

Figure 1. SEM photograph of fabricated thin film edge emitter triode with continuous edge.

Figure 2. SEM photograph of thin film edge emitter triode which utilizes a comb emitter structure.

Figure 3. Test setup for performing triode measurements in high vacuum.

Figure 4. Transfer characteristics of vacuum transistor showing triode-like characteristics. The device has four fingers that are ~1 μm wide.

Figure 5. Output characteristics of vacuum transistor showing triode-like behavior. The output conductance depends on the anode voltage. The device has four fingers that are ~1 μm wide.

Figure 6. Modulation test set-up for the vacuum transistor.

Figure 7. Vacuum Transistor Modulation Test. The bottom trace in each plot is the input and the top trace is the output. The test conditions are labeled in each case. The input was maintained at the same level. The figures show the output increasing with increasing emitter current and control voltage.

Device Fabrication I

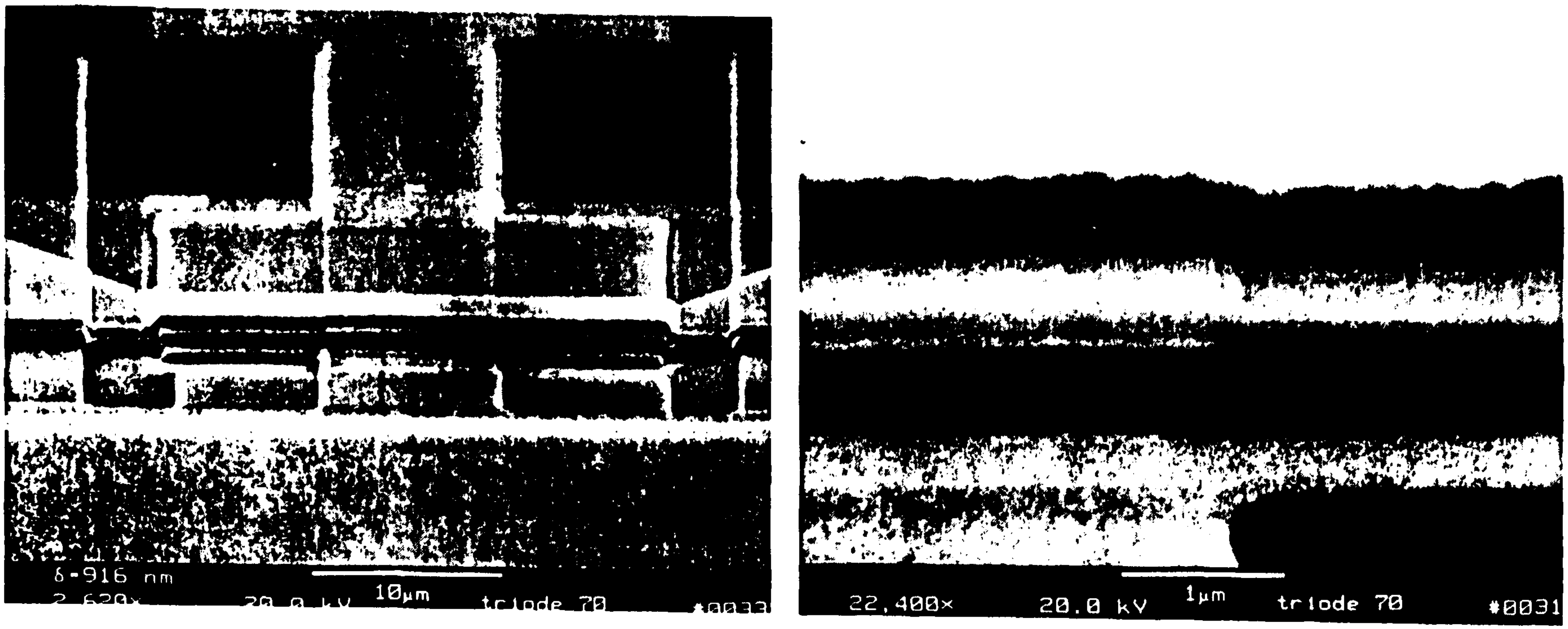


Figure 1. SEM photograph of fabricated thin film edge emitter triode with continuous edge.

Device Fabrication II

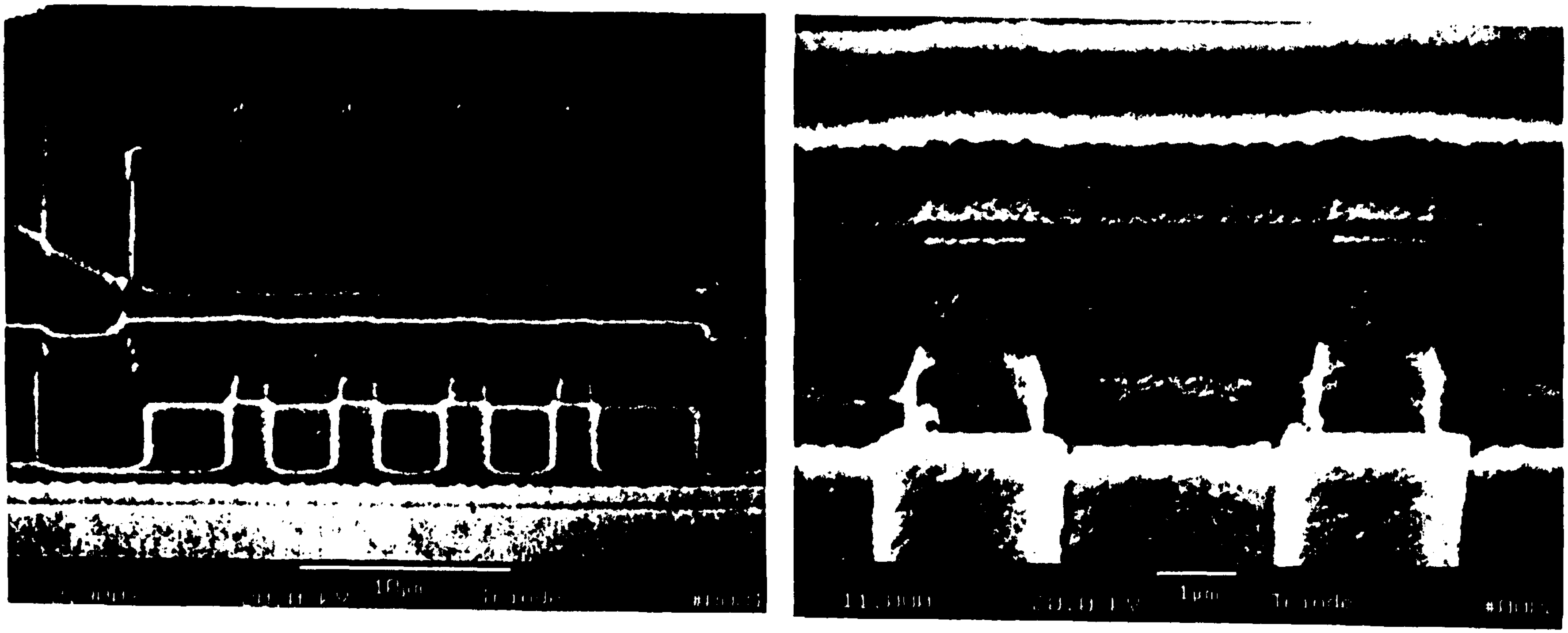


Figure 2. SEM photograph of thin film edge emitter triode which utilizes a comb emitter structure.

Vacuum Microelectronics

Vacuum Transistor Test Set-up

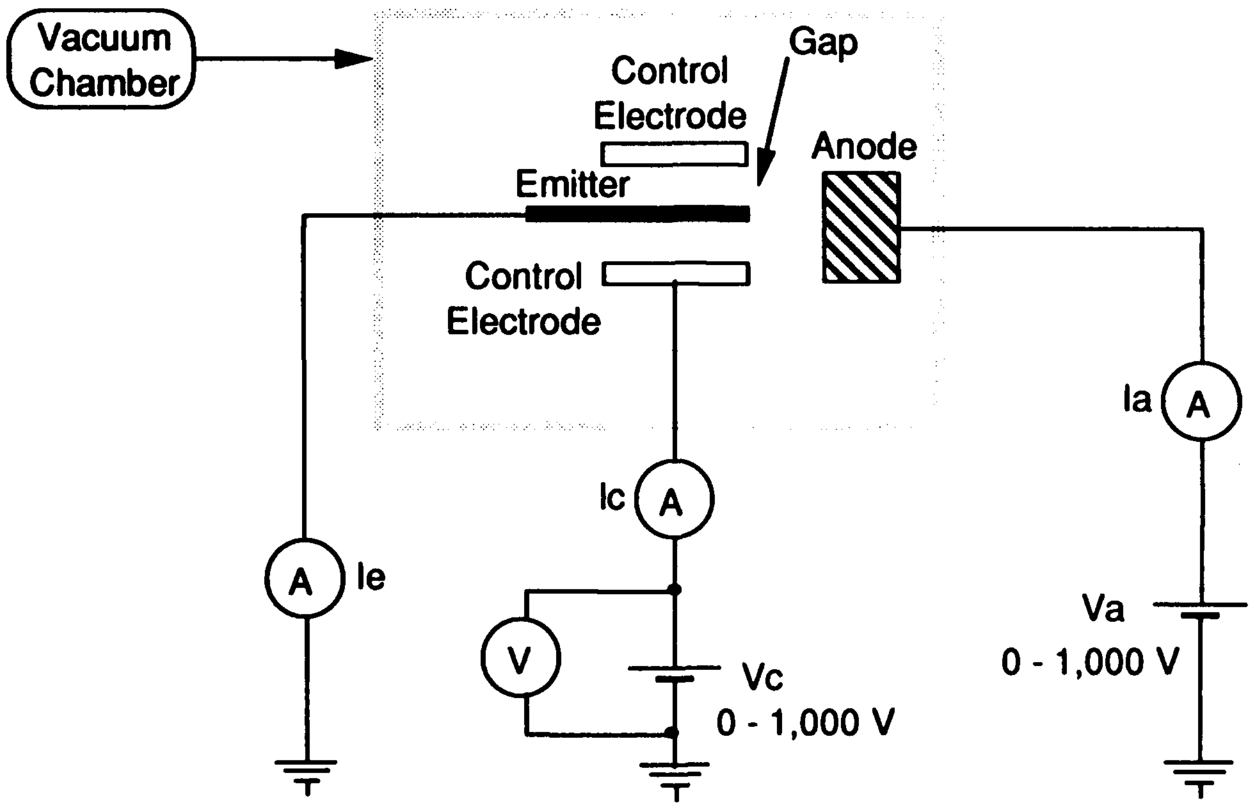


Figure 3. Test setup for performing triode measurements in high vacuum.

RF Vacuum Microelectronics

Vacuum Transistor Transfer Characteristics

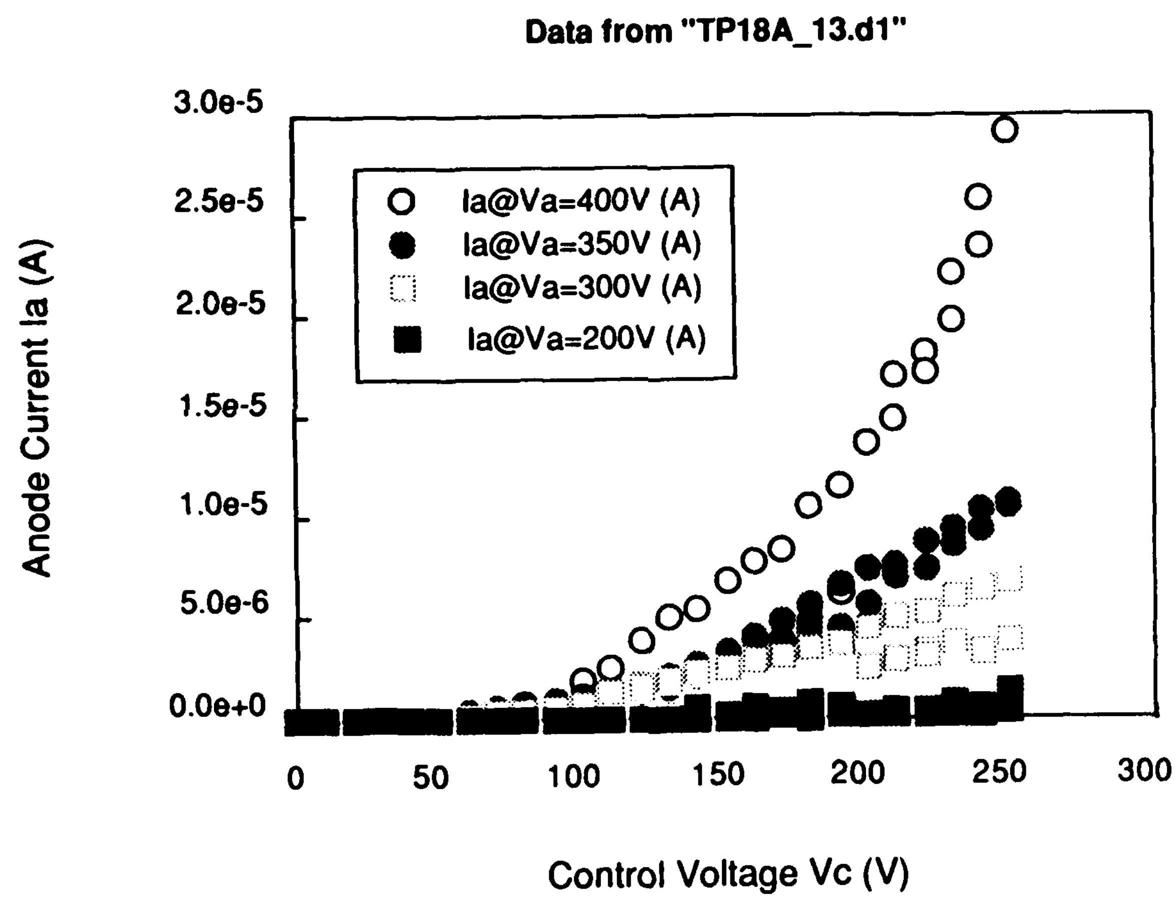


Figure 4. Transfer characteristics of vacuum transistor showing triode-like characteristics. The device has four fingers that are ~1 μm wide.

Vacuum Transistor Output Characteristics

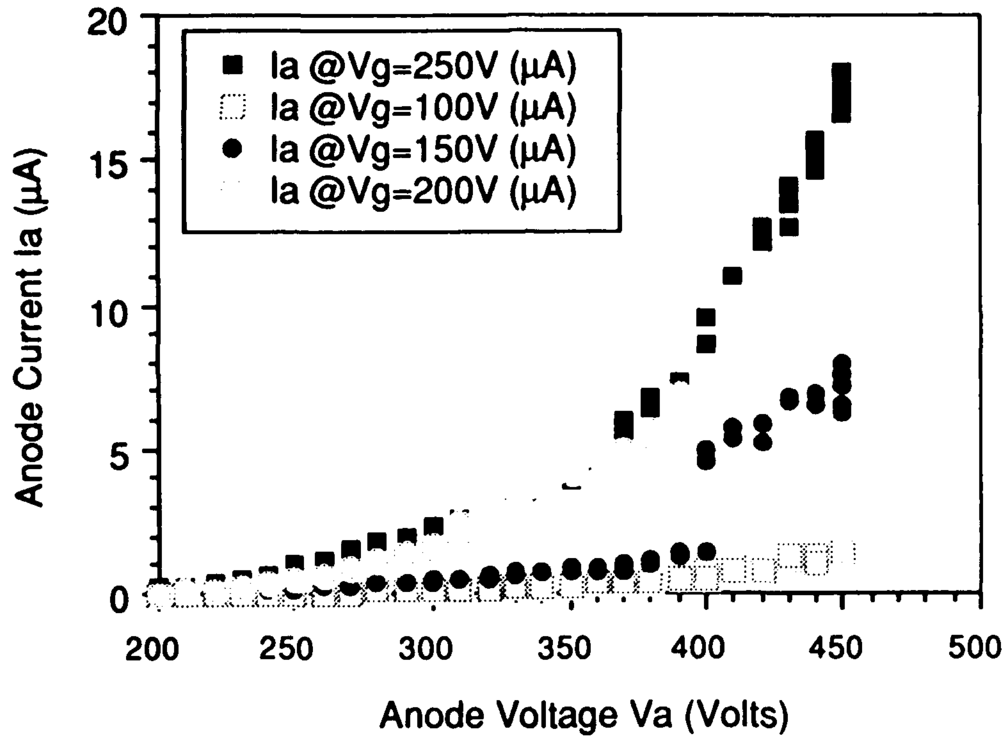


Figure 5. Output characteristics of vacuum transistor showing triode-like behavior. The output conductance depends on the anode voltage. The device has four fingers that are ~1 µm wide.

Vacuum Transistor Modulation Test Set Up

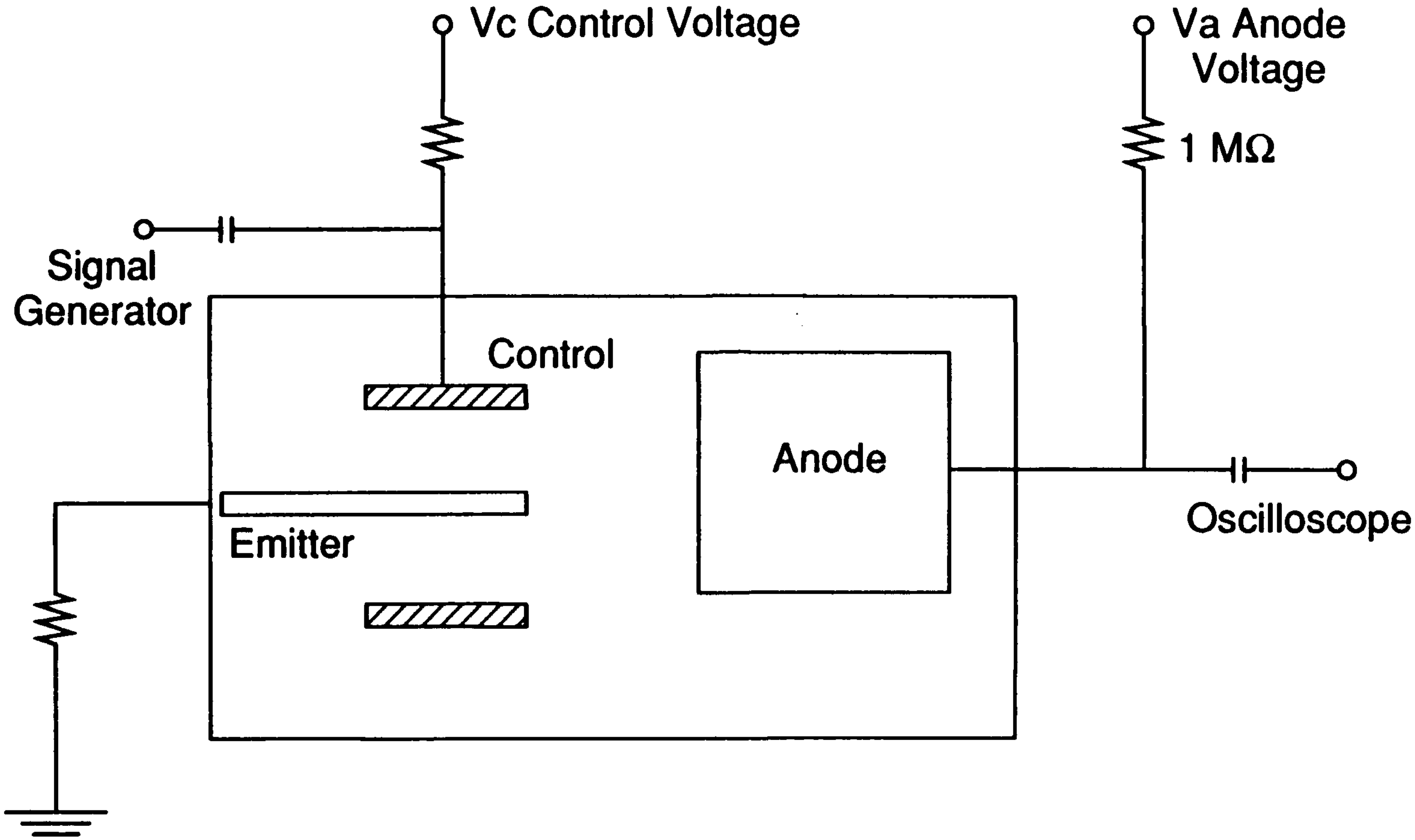
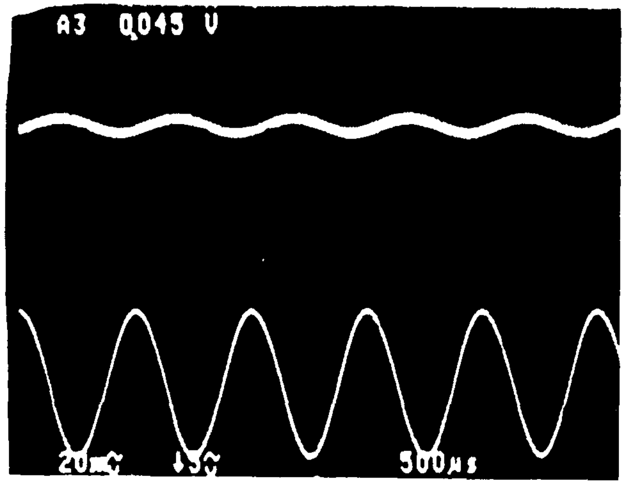
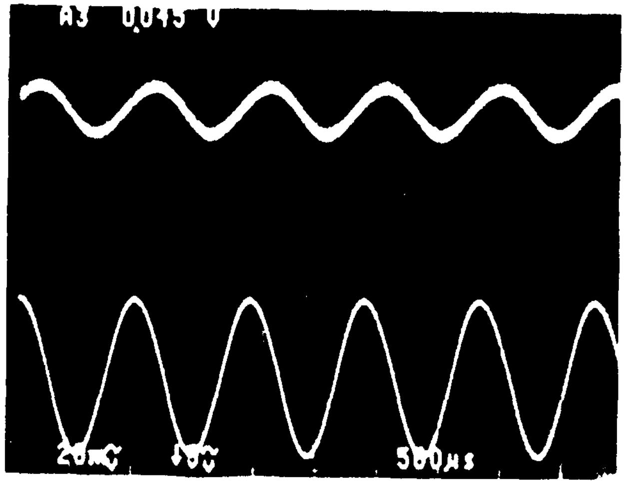


Figure 6. Modulation test set-up for the vacuum transistor.

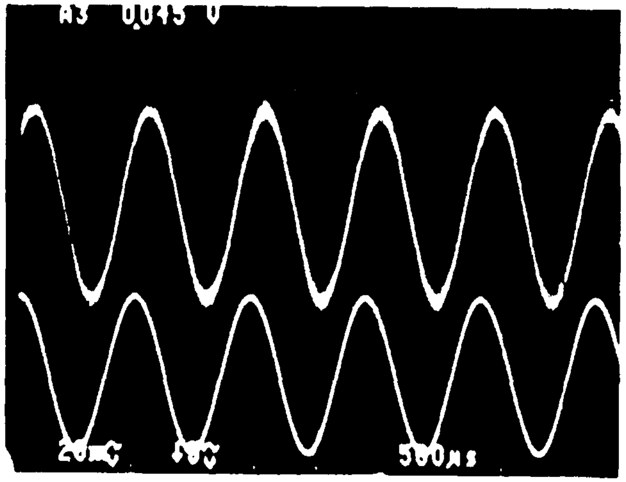
Vacuum Transistor Modulation Test



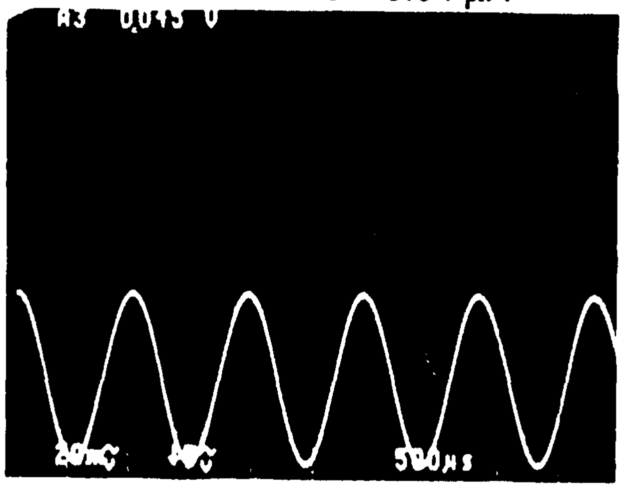
Va = 0
Vc = 0



Va = 350 V
Vc = 70 V Ve = 0.04 μA



Va = 350 V
Vc = 80 V Ie = 0.56 μA



Va = 350 V
Vc = 150 V Ie = 2 μA

Figure 7. Vacuum Transistor Modulation Test. The bottom trace in each plot is the input and the top trace is the output. The test conditions are labeled in each case. The input was maintained at the same level. The figures show the output increasing with increasing emitter current and control voltage.

Nanometer Scale Thin-Film-Edge Emitter Devices With High Current Density Characteristics

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ABSTRACT

We report the demonstration of thin-film-edge emitter devices with reproducible high current density characteristics. The demonstrated devices include both diodes and triodes with thin film emitters, anodes and control electrodes on the same wafer. Contrasted with the usual vertical FEA structures, this particular triode design invokes two dimensional vertical symmetry for the extraction electrodes using multi-layer thin-film deposition and patterning techniques. Emission currents as high as 400 μA per edge have been demonstrated and current densities as high as 10 μA/μm of edge width.

INTRODUCTION

Conventional distributed interaction thermionic emission cathode tubes have demonstrated power outputs exceeding 1 megawatt for a wide range of microwave frequencies while solid state field effect transistors continue to break previous records for low noise performance up to 100 GHz. For many applications, these devices are quite appropriate. However, the tube cost, weight and power supply complexity as well as power outputs exceed many budget requirements. Solid state devices, operating at low voltages, may have insufficient power outputs. The field emission triode may offer advantages as a compromise device with more power output than the solid state approach with simpler power supplies and lighter weight than other vacuum tubes. The structure most commonly associated with the Field Emission Array is one which consists of a micron size cell with a cone-like vertical field emitter and an integrated circular aperture which surrounds the emitter tip [1,2]. While most of this work to date has focused on the vertical field emission devices, lateral emitters formed by planar lithography and surface micromachining are just beginning to be studied [3,4]. For high frequency operation, the most important figure of merit is f_τ (unity current gain cut-off frequency) which is proportional to the ratio of the transconductance to the input capacitance. Compared with conventional semiconductors, FEA based devices have lower capacitance because of the their lower effective dielectric constant. This implies that FEAs require lower transconductance to achieve the same f_τ assuming the same capacitance level. However for vertical FEAs having the cone like structure, the device capacitance is dominated by a parasitic component governed by the active and inactive area of the FEA and it is usually large compared to the intrinsic capacitance of the device. An approach to reduce the effect of parasitic capacitance is to scale devices to smaller geometries. The transconductance / unit area will increase at a faster rate than the capacitance leading to increased f_τ. However with this scheme, the capacitance is not independent of the transconductance. An approach that allows simultaneous increase in transconductance and decrease of capacitance is the lateral thin-film edge emitter shown in Figure 1.

Side View of DCE Triode

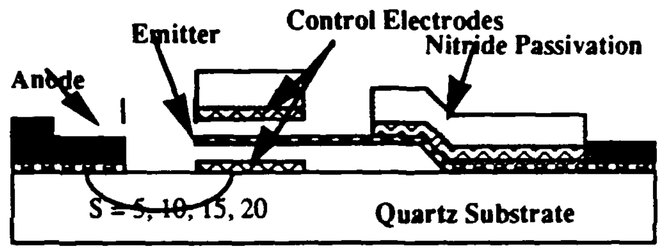

Figure 1. Vacuum Transistor with Dual Control Electrodes.

THIN-FILM-EDGE EMITTER VACUUM TRANSISTOR

Contrasted with the usual vertical FEA structures, this particular triode design invokes two dimensional vertical symmetry for the extraction electrodes using multi-layer thin-film deposition and patterning techniques. A central nanometer scale thick edge-emitter film is sandwiched between two extraction electrodes (one above and one below). The thin-film-edge emitter maximizes transconductance, g_m and minimizes the extraction electrode capacitance C because (i) emission occurs along a thin film edge, thus enabling the use of very narrow extraction electrodes with a small area per unit current and (ii) transconductance is maximized because the very small radius of curvature is ensured by the thin dimension of the emitter film. These two factors ultimately lead to improved f_τ. In essence, the edge has one key advantage : it allows more emitting points / area to be packed into the area between its control electrodes than it is possible with point emitters surrounded by extraction electrodes. This design and fabrication methodology has several other major

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advantages compared to the classical vertical FEA design: (1) The radius of curvature of the electron emitter must be less than or equal to the thickness of the thin film emitter metallization. The thickness of the thin film can be controlled to nanometer dimensions by a number of known deposition processes. (2) The distance between the control electrodes and the emitter is determined by the thickness of deposited insulator thin films. These thicknesses can also be controlled to nanometer tolerances by deposition processes. (3) The total electron path can be potentially much shorter than vertical designs. This distance, which determines the total transit time, might be important for high frequency operation. (4) No critical dimension is dependent on high resolution lithography. Finite element based simulation of field emitter structures has been used to estimate the electric fields, currents and temperatures of typical devices to enhance our understanding of their operation and suggest techniques to improve their performance.

The device shown in Figure 1 is a 3D microstructure and was fabricated with several nanometer scale depositions, microelectronic patterning and surface micromachining. The self-aligned microstructure techniques used in the fabrication of the 3D devices brings the precise geometries of integrated circuit processing to the problem of making vacuum devices. The devices are 5 µm wide and have 300 Å thick TiW emitters. The emitter is supported on both sides by a 1500 Å thick layer of silicon nitride for mechanical stability. The emitter / control electrode spacing is 0.7 µm. The upper control electrode is supported on the top side by a thick nitride layer because of the expected electrostatic forces on the control electrode when the devices are biased. The sacrificial layer is removed by buffered HF.

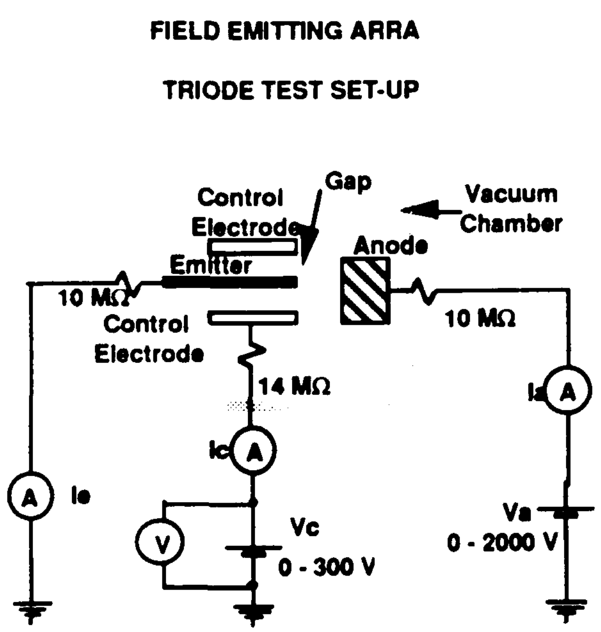

Figure 2. Vacuum Transistor Test Set-Up.

Figure 2 shows the test set up for the vacuum transistor. The vacuum was maintained at a pressure less than 1 x 10^{-8} Torr. Figures 3 and 4 show the I-V characteristics and Fowler Nordheim plot of a vacuum transistor. The device turns on at 70 V and at a gate voltage of 180V the emitted current is 2 µA. The corresponding anode voltage is 400 Volts. Figure 5 is a plot of the transconductance and it shows a maximum transconductance of about 0.1 µS. Figure 6 is the IV characteristics corresponding to an anode voltage of 600 V indicating a maximum current of 3 µA with a transconductance of 0.2 µS.

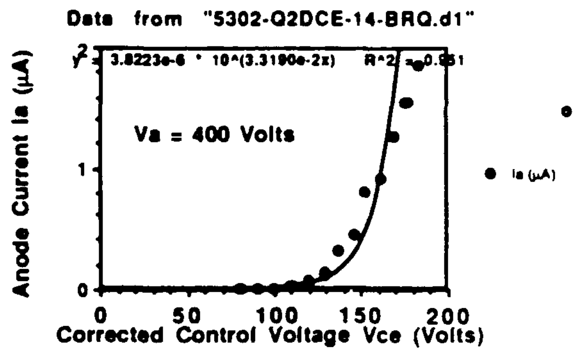

Figure 3. I-V characteristics of a Vacuum Transistor. Anode Voltage is 400 Volts.

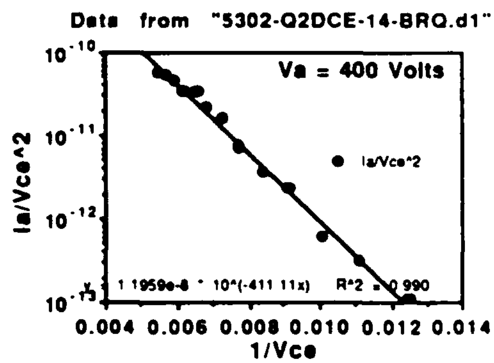

Figure 4. Fowler Nordheim Plot of a Vacuum Transistor. Anode Voltage is 400 Volts.

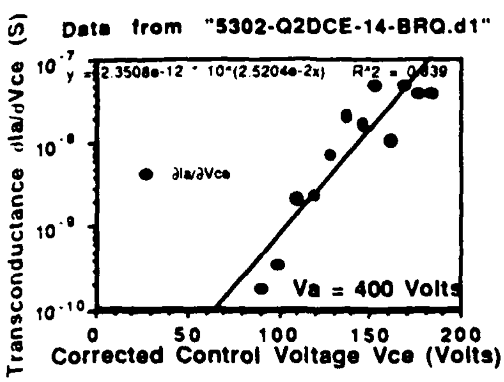

Figure 5. Transconductance of a Vacuum Transistor. Anode Voltage is 400 Volts.

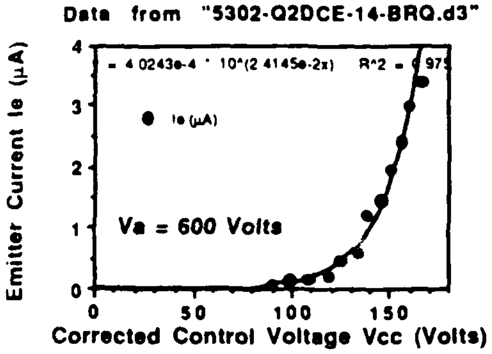

Figure 6. I-V Characteristics of a Vacuum Transistor. Anode Voltage is 600 Volts.

THIN-FILM-EDGE EMITTER DIODE

The critical part of the vacuum transistor is the thin-film edge emitter. To electrically characterize the film's field emission characteristics, we used special diode structures with submicron spacing between the emitter film edge and an in-plane anode. Figure 7 is a schematic of the thin-film edge vacuum diode. Figure 8 shows the current voltage characteristics for a 300 Å TiW emitter. Table 1 is a summary of the maximum current obtained for each device width and the maximum current density. We demonstrated a maximum current of 385 µA for a device that is 100 µm wide and maximum current density of 9.6 µA/µm of width for a device that is 5 µm wide. There is a decrease in the maximum current density as the edge width increases. It can be concluded that emission from the edge is not occurring just at the corners, however the corners may have a dominant influence. We did long term tests on the devices by measuring the voltage required to maintain 50 µA emission from a 100 µm wide edge. Data was taken every 5 seconds. The device was still operational after more than 72 hours.

Device Width	Max Current	Current Density
5 µm	48 µA	9.6 µA / µm
10 µm	59 µA	5.9 µA / µm
20 µm	165 µA	8.3 µA / µm
50 µm	288 µA	5.8 µA / µm
100 µm	383 µA	3.8 µA / µm

Table 1. Summary of Emission Current and Emission Current Density.

PREDICTED PERFORMANCE

The equivalent circuit for our devices is shown in Figure 9. We extracted the transconductance per unit width of the diode and triode devices and using a conservative transconductance value of 0.1 µS / µm and a current of 10 µA / µm of width and also assuming a gate width of 0.25 µm, we obtain from our modeling a predicted f_{max} of about 1 GHz as shown in Figure 10. The performance expected with various multiples of these currents are also displayed in the same figure. We expect the transconductance per unit width to increase as the device and process is optimized. The transconductance will increase if the radius of curvature of the emitter and the emitter / extraction electrode distance is decreased.

SUMMARY

In this paper we report the demonstration of thin-film-edge emitter devices with reproducible high current density characteristics. The demonstrated devices include both diodes and triodes with thin film emitters, anodes and control electrodes on the same wafer. The results indicate the possibility of a new type of microwave power sources with power handling capability of power tubes and high frequency performance of semiconductors.

ACKNOWLEDGEMENT

We acknowledge the support of DARPA under the RF Vacuum Microelectronics Program.

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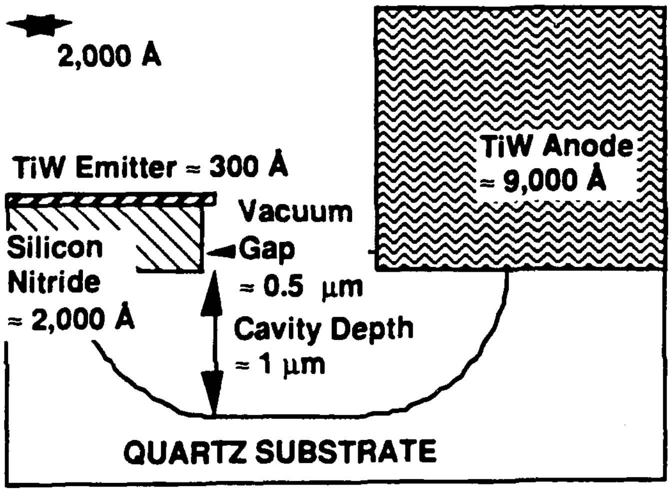

Figure 7. Thin-Film-Edge Emitter Vacuum Diode.

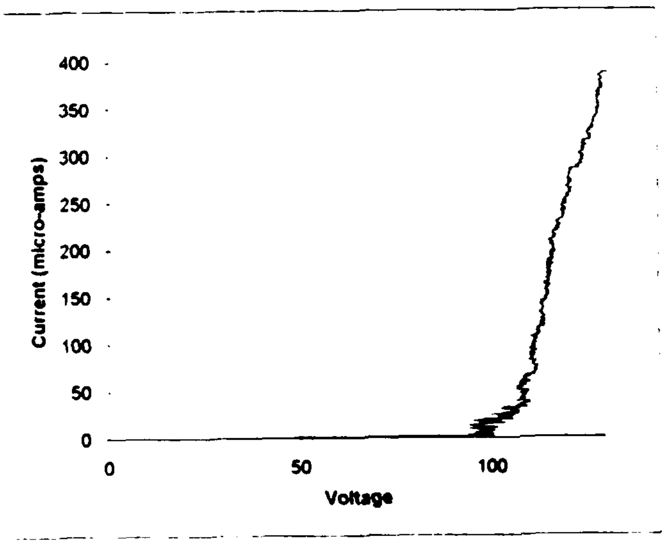

Figure 8. I-V characteristics of a 300 Å Thick TiW emitter. Edge width is 100 µm.

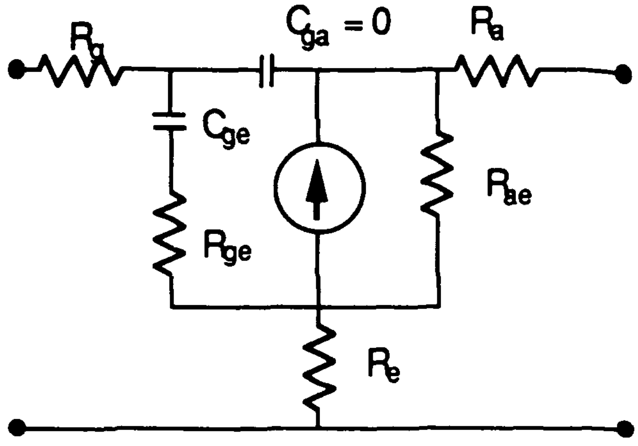

Figure 9. Equivalent Circuit Used in Calculating Performance.

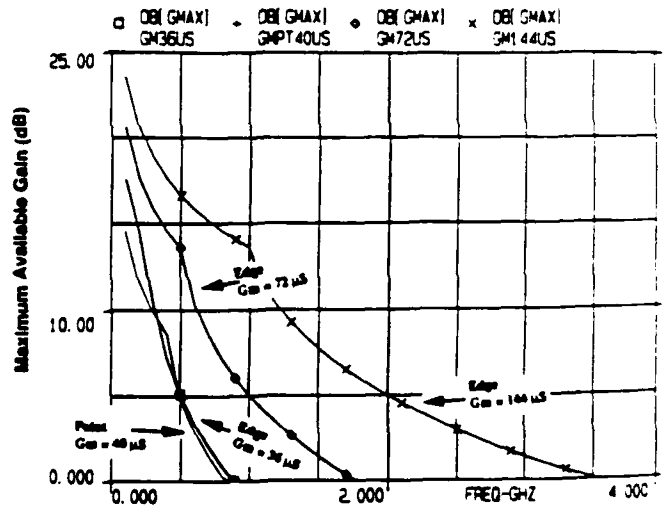

Figure 10. Predicted Maximum Available Gain for Devices with Current Densities Reported Here. A comparison is made to the array of points with comparable transconductance.